

# Secular Trends of Precipitation Amount, Frequency, and Intensity in the United States



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## ABSTRACT

Twentieth century trends of precipitation are examined by a variety of methods to more fully describe how precipitation has changed or varied. Since 1910, precipitation has increased by about 10% across the contiguous United States. The increase in precipitation is reflected primarily in the heavy and extreme daily precipitation events. For example, over half (53%) of the total increase of precipitation is due to positive trends in the upper 10 percentiles of the precipitation distribution. These trends are highly significant, both practically and statistically. The increase has arisen for two reasons. First, an increase in the frequency of days with precipitation [ $6 \text{ days } (100 \text{ yr})^{-1}$ ] has occurred for all categories of precipitation amount. Second, for the extremely heavy precipitation events, an increase in the intensity of the events is also significantly contributing (about half) to the precipitation increase. As a result, there is a significant trend in much of the United States of the highest daily year-month precipitation amount, but with no systematic national trend of the median precipitation amount.

These data suggest that the precipitation regimes in the United States are changing disproportionately across the precipitation distribution. The proportion of total precipitation derived from extreme and heavy events is increasing relative to more moderate events. These changes have an impact on the area of the United States affected by a much above-normal (upper 10 percentile) proportion of precipitation derived from very heavy precipitation events, for example, daily precipitation events exceeding 50.8 mm (2 in.).

## 1. Introduction

In many areas of the United States during recent years, there has been a notable number of catastrophic flooding episodes. A few examples include the 1993 flooding event along the Mississippi, the New England floods during the autumn of 1996, the winter floods of 1997 in the Pacific Northwest and California, and the 1997 spring floods along the Ohio River and the Red River Valley. Previous work (Karl et al. 1996) has documented an increase in the proportion of the area of the United States affected by a much above-normal frequency of extreme precipitation events, for example,  $> 50.4 \text{ mm day}^{-1}$  (or 2 in.). A

thorough analysis of how precipitation is changing in the United States, however, has not been provided.

Changes in precipitation have most often been quantified in terms of changes in the total precipitation over long averaging periods, for example, annually, seasonally, and occasionally monthly. Such statistics (Karl et al. 1993; Groisman and Easterling 1994; IPCC 1990, 1996), although quite useful for many applications, do not reveal important aspects of how precipitation changes within such a long averaging period. After all, most precipitation events in the midlatitudes last a few days at most.

It would be remiss not to mention some notable work that has emphasized changes in precipitation intensity (Englehart and Douglas 1985; Diaz 1991; Yu and Neil 1991; Nicholls and Kariko 1992; Karl et al. 1995; R. Suppiah and K. Hennessy 1998, manuscript submitted to *Int. J. Climatol.*; Mearns et al. 1995). In these analyses, however, there has been no standard technique of investigating precipitation intensity. For example, R. Suppiah and K. Hennessy (1998, manuscript

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submitted to *Int. J. Climatol.*) calculate trends equivalent to the number of days with precipitation to understand how the frequency of precipitation contributes to changes of precipitation, but only the trends of the 90th and 95th percentiles of daily precipitation amount are used to calculate how the intensity of precipitation may be affecting the trend. Nicholls and Kariko (1992) define precipitation intensity as the mean rainfall per day, but define a rainfall event as any period of days with consecutive rainfall. Mearns and Giorgi (1995) analyze on a monthly basis the number of precipitation days, the average rainfall per rain day (what they define as intensity), and the average rainfall per day.

Although there is no single method of analysis that can comprehensively cover all the important aspects of how precipitation changes over the course of time, it is fairly apparent that more consideration needs to be given to the type of questions various analyses can address. For example, a rather fundamental question might be related to how much of any precipitation increase or decrease is attributable to changes in the frequency of precipitation versus intensity of precipitation. For example, increased precipitation could be derived from simply more days during the year with precipitation, and they may be equally distributed for all quantiles<sup>1</sup> of daily precipitation amount. Alternatively, one could also envision a situation where the number of days with precipitation does not change, but the amount of precipitation changes for all, or a limited number of quantiles.

## 2. Data

There are several datasets that are used in this analysis. The primary dataset is the daily precipitation dataset used by Karl et al. (1996). This dataset consists of 182 stations across the contiguous United States. Of these 182 stations, 134 are part of the U.S. Historical Climate Network (HCN, Hughes et al. 1993). An additional 48 stations were added to improve data coverage in the western United States. Detailed station histories for all of these stations indicate that standard 8 in. precipitation gauges have been used throughout the twentieth century at all locations. This dataset is referred to as the HCN special network

(HCNs). The data from these stations span the period 1910–96, but there is some missing data, and some stations do not have data back through 1910. To prevent missing data from introducing any bias, Karl et al. (1995) describe a procedure that was used to estimate missing data. Basically, a gamma function is fit to each station's daily data for each month of the year. To determine if precipitation occurs on any missing day, a random number generator is used such that the probability of precipitation is set equal to the empirical probability of precipitation during that month. If precipitation occurs, then the gamma distribution is used to determine the amount that falls for that day, again using a random number generator.

The other two datasets that are included in this study are used primarily to serve as a cross check against the 182 daily dataset. This includes the climatological state divisional precipitation data (Guttman and Quayle 1996), which are monthly averages based on all reporting stations in the United States. In some years and months, this network reaches over 7500 stations. Most of these stations are cooperative weather stations that have not changed in instrumentation during the twentieth century, unlike the first-order stations, which have been affected by new automated instruments and the introduction of wind shields (Karl et al. 1993). These data span the period of the HCNs data, but there is an uneven number of stations that enter and leave the network during the course of the twentieth century, possibly contributing to some bias in trends. The other dataset (TD3200) consists of 3091 stations in the United States that reported daily precipitation and passed our completeness criterion. The period of record is shorter for these data, spanning the years 1948–95, and each station had to have at least 80% of all data present. The TD3200 data were subjected to the standard National Climatic Data Center (NCDC) data checks as given in TD3200 documentation.

## 3. Methods

### a. Spatial averages

The HCNs daily precipitation data as well as the TD3200 data were arithmetically averaged into  $1^\circ \times 1^\circ$  grid cells. These grid cells were then area weighted to calculate changes of precipitation for nine regions across the United States. A national average was derived from these nine regions by area weighting the values within each region on a monthly basis. All sea-

<sup>1</sup>The value of any quantile ( $Q$ ) in a sample is given by the ordered data values themselves. The order of the quantile is given by  $P_i = (i - 0.5) n^{-1}$ , where  $i = 1$  to  $n$ , and  $n$  is the sample size. So  $Q(0.5)$  is the median,  $Q(0.25)$  is the first quartile, etc.

sonal averages are derived from the totals of each month where the standard seasons apply, for example, winter (December–February), spring (March–May), etc. The CD data were area weighted into regional and subsequently into national averages from 344 divisional averages.

#### *b. Precipitation assessment*

Changes in precipitation amount can occur from a change in the frequency of precipitation events, the intensity of precipitation per event, or any combination thereof. Precipitation intensity is defined here simply by the amount of precipitation associated with specific quantiles of the precipitation distribution. Percentiles near 100 represent very intense precipitation and those near zero very light precipitation events. Daily precipitation totals are treated as precipitation events.

It is possible to estimate the proportion of any trend in total precipitation that is attributable to changes in frequency versus changes in precipitation intensity. This is calculated for the frequency component by determining the average precipitation amount per event ( $\bar{P}_e$ ) and the trend in the frequency of events ( $b_f$ ). Then the change in precipitation due to the trend in the frequency of precipitation events ( $b_e$ ) is simply defined by

$$b_e = \bar{P}_e(b_f). \quad (1)$$

In this analysis,  $b_e$  is expressed as (mm yr<sup>-1</sup>) or (mm season<sup>-1</sup>) or as (a % of the mean seasonal or annual total precipitation), for example, (mm day<sup>-1</sup>) (day yr<sup>-1</sup>) = mm yr<sup>-1</sup>. For the intensity component, the trend is directly calculated as a residual using the expression

$$b_i = b - b_e, \quad (2)$$

where  $b$  is the trend in total precipitation for the frequency band or intensity component.

For comparative purposes, trends of total precipitation are expressed as a percent of mean precipitation for months, seasons, annually, etc. The full period of record is used in this analysis to calculate the expected mean total precipitation.

Expressions (1) and (2) are insufficient, however, to adequately describe the nature of precipitation variations and change. For example, it would not be possible to know whether the change in precipitation frequency was due to a change in the number of days with very heavy precipitation or light precipitation amounts. Similarly, it would be uncertain as to whether the pre-

cipitation intensity had increased across all quantiles of the distribution or just a few, such as the very heavy precipitation intensities or some of the more moderate intensities, for example, around the median.

Information about these kinds of changes can be obtained by simply applying (1) and (2), not to the full dataset, but to specific class intervals defined by the quantiles of the precipitation distribution. In this analysis the precipitation distribution is categorized into 20 class intervals, where each class interval has a width of five percentiles. The percentile defined intervals range from the lowest percentile to the 5th percentile, the 5th to the 10th percentile, . . . and the 95th to the highest percentile. These percentiles were defined for each station on a monthly, seasonal, and annual basis. So, for each season of interest, (1) and (2) is directly applied 20 times to the ensemble of all values falling within each of these class intervals for the time period of interest, that is, 1910–96.

Trends of precipitation can also be calculated for specific quantiles. One particular statistic of interest is the trend of the highest daily precipitation amount. In this analysis, we find the highest and median precipitation amount each month for all years of record and then calculate the trend of these values. The amount of precipitation associated with the trend is expressed as a percentage of the mean of these year-month total precipitation amounts, for example, either the highest monthly daily total or the median of the daily totals.

Another way to analyze how precipitation is changing is to evaluate the trends of the proportion of precipitation falling in a specific class interval compared with the total mean precipitation. This statistic also provides information about relative changes within the distribution unrelated to changes in the mean.

Another aspect of precipitation change that is important in some applications relates to trends in the area affected by heavy or extreme precipitation amounts. In this analysis, the upper 10 percentile is defined as a very heavy precipitation event. Similar to the analysis of Karl et al. (1996), the area of the United States affected by a much greater than normal (upper 10 percentiles) frequency of the proportion of total annual precipitation derived from very heavy precipitation was calculated for each station. The trend in the area affected by these events is calculated on a national and regional basis. In this analysis, the upper 10 percentile has been chosen as the class limit, but obviously other class limits could have been selected.

## 4. Results

Precipitation has increased across the United States over much of the twentieth century (Table 1). The increase is most pronounced during the spring and autumn but is also apparent during summer. Wintertime precipitation amount has increased only slightly. The sensitivity of the trend to the dataset used is reflected in Table 1. It is apparent that the annual increase in precipitation is fairly stable from one dataset to the next, but for seasonal trends, even when the trends are statistically significant, differences among the datasets can be up to 4% per century. Given the variability of trends between the datasets from TD3200 and CD (Table 1), the use of the higher quality, lower density HCNs is not grossly affected by its relatively low coverage.

Figure 1 depicts how the change in precipitation has occurred. In such an analysis, it is possible to understand the contribution of light, medium, and heavy precipitation amounts to the total trend. The sum of the trend across all class intervals is identically equal to the trend of the total precipitation. Nationally, on an annual basis, over half of the precipitation increase is due to the increase of precipitation within the upper 10% of all the daily precipitation amounts, for example, class intervals 90 and 95 in Fig. 1a. The trends in these two categories are highly significant based on Kendall's nonparametric  $\tau$  statistic<sup>2</sup>, and Fig. 2 depicts the time series from which the trends were derived. Over half (53%) of the total trend is due to the upper 10% of daily precipitation events, despite the fact that they only constitute about 35% or 40% of the total annual precipitation across the United States. Given this, the trends in these percentiles are larger than might be expected. The con-

TABLE 1. United States national precipitation trends expressed in terms of percent of the mean per century and (top line) millimeters per century (bottom line) in each row. Statistical significance ( $\alpha = 0.05$ ) is reflected by bold numbers based on a nonparametric Kendall  $\tau$ -test. Datasets are HCNs, Climate Division (CD) data (the U.S. climatological division dataset), and TD3200.

Dataset	Time period	Annual	Winter	Spring	Summer	Autumn
HCNs	1910–96	<b>10.1</b>	2.8	<b>11.2</b>	<b>11.6</b>	<b>14.3</b>
		<b>81</b>	5	<b>23</b>	<b>24</b>	<b>29</b>
CD	1910–96	<b>10.0</b>	−0.3	<b>14.3</b>	6.6	<b>19.5</b>
		<b>76</b>	−1	<b>29</b>	14	<b>34</b>
CD	1901–96	<b>7.7</b>	1.1	<b>9.3</b>	2.1	<b>19.2</b>
		<b>65</b>	2	<b>19</b>	4	<b>40</b>
TD 3200	1948–95	<b>16.9</b>	−7.2	23.6	11.8	<b>37.7</b>
		<b>128</b>	−12	<b>48</b>	25	<b>66</b>
HCNs	1948–95	<b>14.7</b>	−7.0	20.0	5.5	<b>40.1</b>
		<b>110</b>	−12	<b>41</b>	11	<b>71</b>
CD	1948–95	<b>19.5</b>	−2.6	23.9	10.3	<b>48.8</b>
		<b>151</b>	−5	<b>49</b>	21	<b>86</b>

tribution to the increase in precipitation due to the heaviest precipitation events is even more pronounced during the summer (Fig. 1), as about half of the increase in summer precipitation is from the highest class interval ( $>$  the 95th percentile). During both spring and autumn (Fig. 1 and Table 1), the same tendency is observed, a significantly large contribution to the total trend from the higher percentile class intervals.

Based on Table 1, it might be tempting to conclude that during winter there has been little change in precipitation frequency or intensity, but Fig. 1 indicates that precipitation from the heaviest categories has increased, although not in a statistically significant manner, but this accounts for all of the increase. The lighter precipitation categories have tended to have slight decreasing trends, partially offsetting the increase from the heaviest categories.

The trends in the frequency of events (Fig. 3) within each of the percentile-defined class intervals indicates that at least a portion of the increase in precipitation is due to an increase in the frequency of events. On an annual basis, virtually every region has a statisti-

<sup>2</sup>Kendall's  $\tau$  statistic for trends tests the nonrandomness of the ranks of the time-dependent data. It is nearly as powerful as Pearson's correlation coefficient in rejecting the hypothesis of no trend in the data, but is insensitive to the distribution of the data.

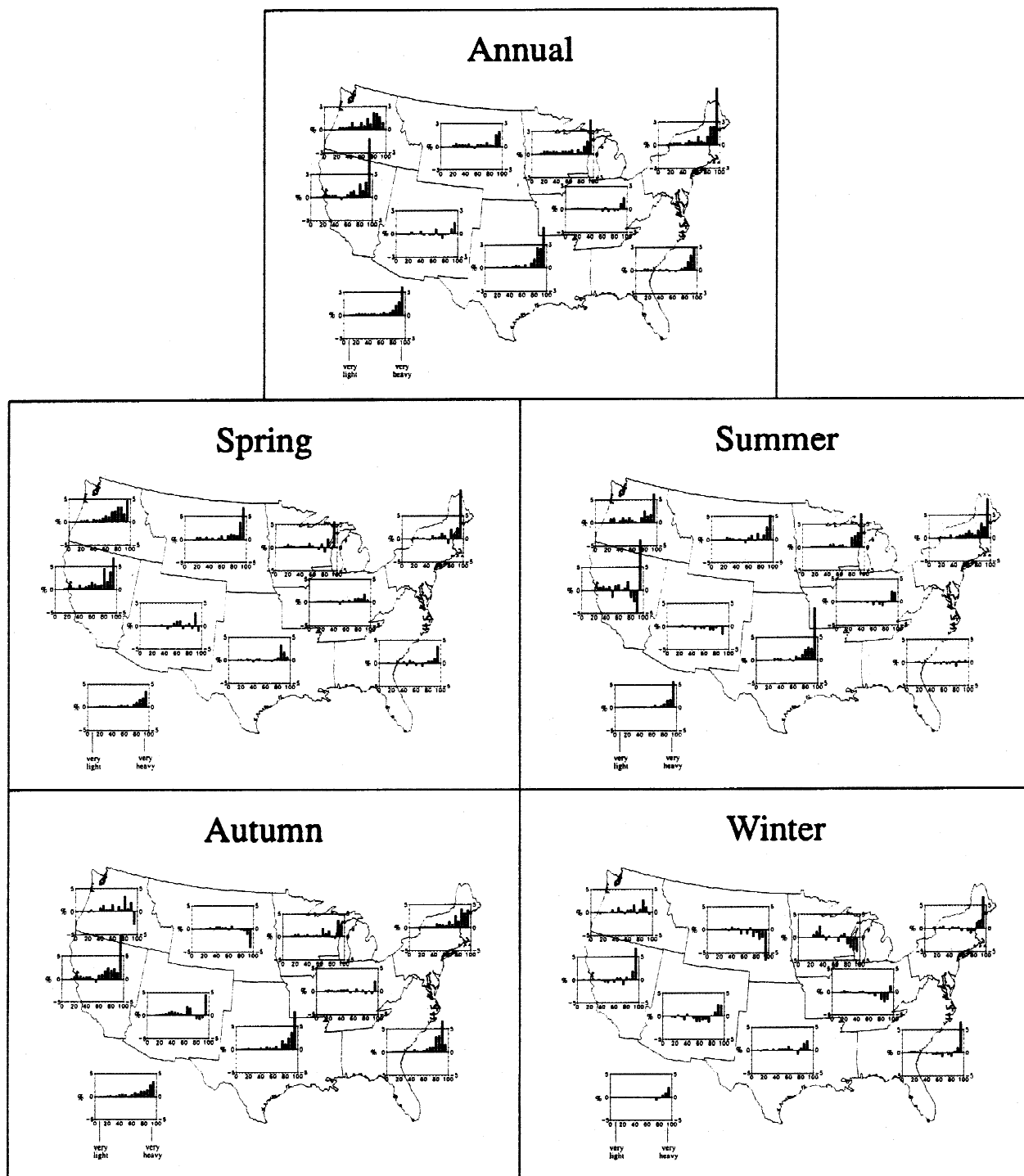


FIG. 1. Trends (1910–96) expressed as percent of mean precipitation per century for various categories of precipitation defined by five percentile class intervals. Value plotted at the 95th percentile represents the trend for the 95th to the highest percentiles, value plotted for the 90th percentile represents the trend for the 90th to the 95th percentile. Value plotted at 5th percentile represents the trend from the lowest percentile to the 5th percentile. The bar chart in the lower left reflects the national average.

cally significant increase in the number of precipitation events. There is a slight tendency, however, for this to be most pronounced for the light precipitation

categories. On a seasonal basis, the summer and winter (Fig. 3) have the smallest increases in frequency, with winter having just a slight increase in precipita-

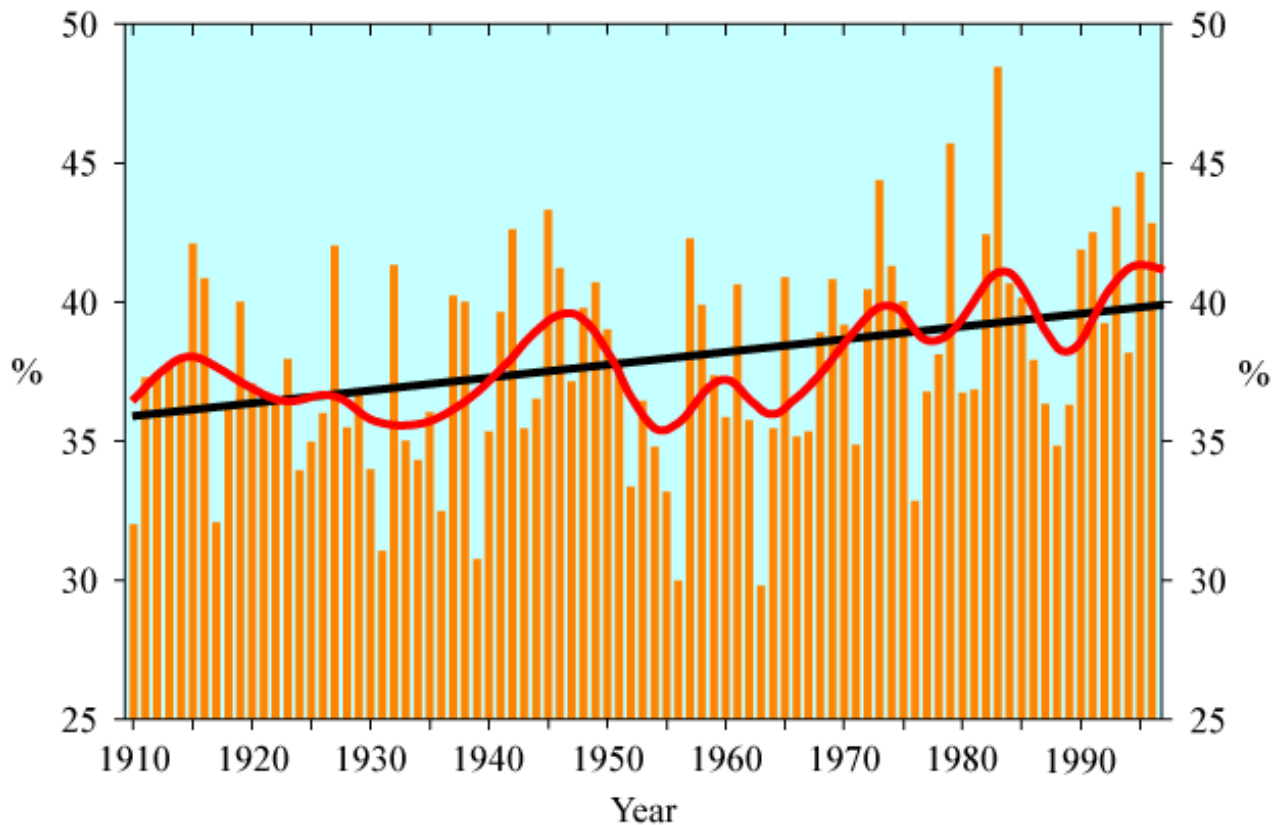


FIG. 2. Time series of the percent contribution of the upper 10 percentile of daily precipitation events to the total annual precipitation area-averaged across the United States. Smooth curve is a nine-point binomial filter, and the trend is also depicted.

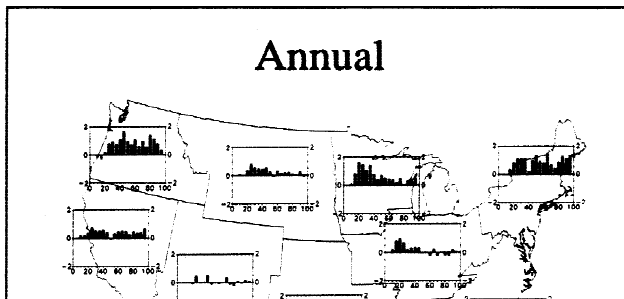
tion frequency ( $< 0.5$  days per century) followed by summer (1.3 days per century). Increases in the days with precipitation were significantly higher for the spring and autumn with 2.2 and 2.3 more precipitation days per century, respectively. These latter increases are fairly evenly spread throughout the precipitation distribution (Fig. 3). Clearly, the total annual increase in precipitation frequency of 6.3 days per century significantly contributes to the increase in precipitation.

Over the entire precipitation distribution, on a national basis, the increase in the number of days with precipitation contributed an amount equal to 87% of the total increase of precipitation. The contribution is strongest for the heavy and extreme precipitation categories ( $> 90$ th percentile) as depicted in Fig. 4. These two categories contributed about one-third of the total increase of precipitation given in Table 1 (10.1% per century). During the spring, summer, and autumn (Fig. 4), many of the large increases in frequency within each of the class intervals are statistically significant.

On an annual basis, trends of precipitation intensity (Fig. 5) reflect increases for the heavy and extreme precipitation categories, but only slight decreases throughout the rest of the distribution. This is apparent in most seasons (Fig. 5), but is particularly noteworthy for the highest precipitation class interval during summer. Here, like the annual increase, the increase in precipitation intensity is statistically significant at the  $\alpha = 0.10$  significance level. For the upper 10 percentiles in the precipitation distribution, representing heavy and extreme precipitation amounts, the contributions to the total precipitation increase related to increased intensity versus frequency are about equal, 47% versus 53%, respectively. This is in contrast to the overall 13% contribution from intensity versus an 87% contribution from frequency to the total precipitation increase.

The trends in the extreme highest precipitation amount for each year-month also reflect the increase in intensity at the highest quantiles (Fig. 6). All areas reflect an increase in precipitation intensity for the highest quantile. Also depicted in Fig. 6 is the tendency for a decrease in precipitation intensity for the more

## Annual



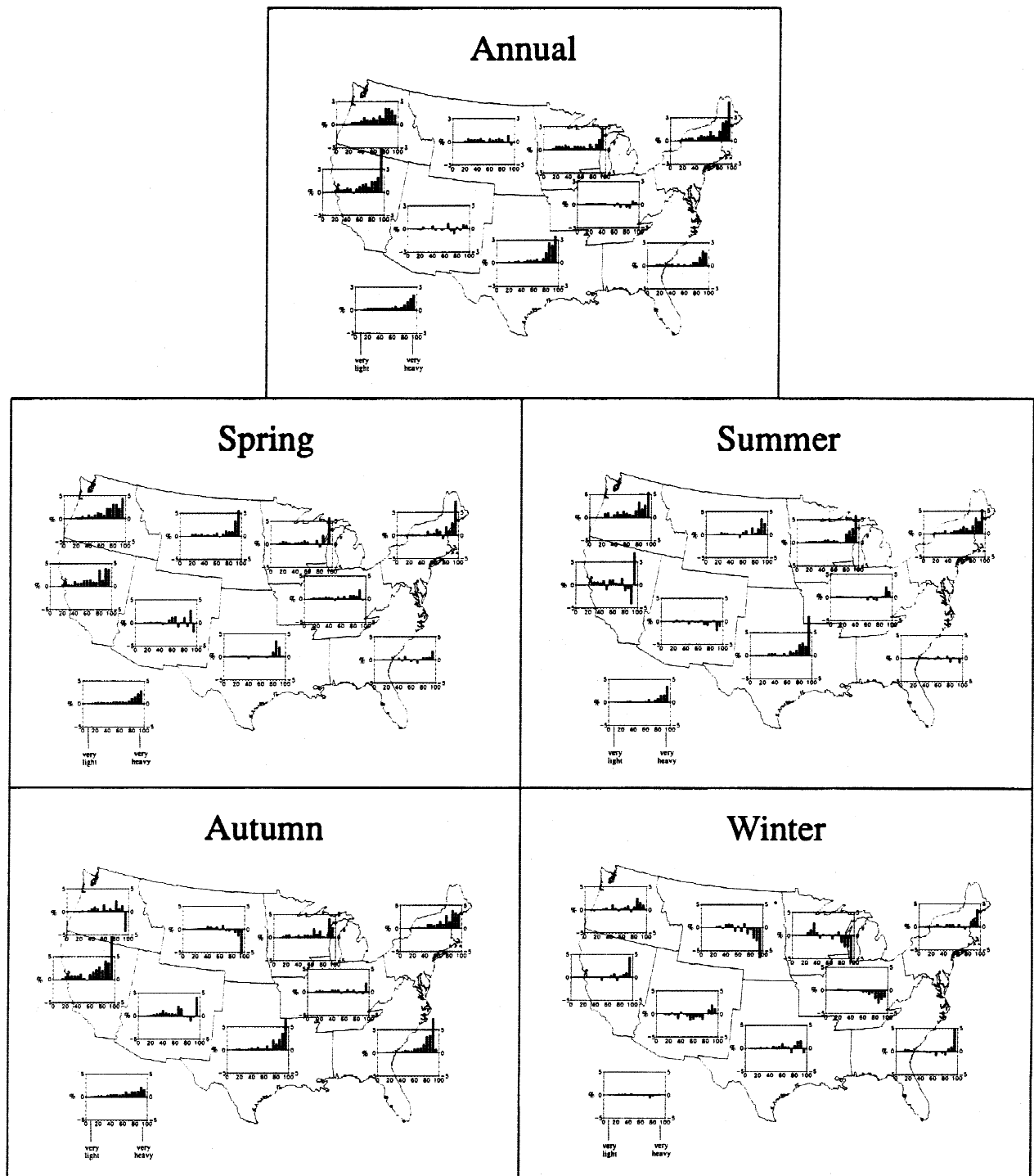


FIG. 4. The contribution to the trends in Fig. 1 attributed to trends in precipitation frequency. Trends are expressed as in Fig. 1.

a change in the precipitation distribution; for example, a change in the shape and/or scale parameters for a gamma distribution fit to daily precipitation amounts. The time series for the national average (Fig. 8) of the proportion of precipitation derived from events exceeding  $50.8 \text{ mm day}^{-1}$  reveals a statistically significant in-

crease (2%) in area affected by a much above-normal frequency of these heavy and extreme events (Fig. 8).<sup>3</sup>

<sup>3</sup>Karl et al. (1996) published a similar time series, but the data presented here is based on an improved  $1^\circ \times 1^\circ$  grid-cell scheme. Trends are unchanged, but annual values differ from earlier work, sometimes substantially.



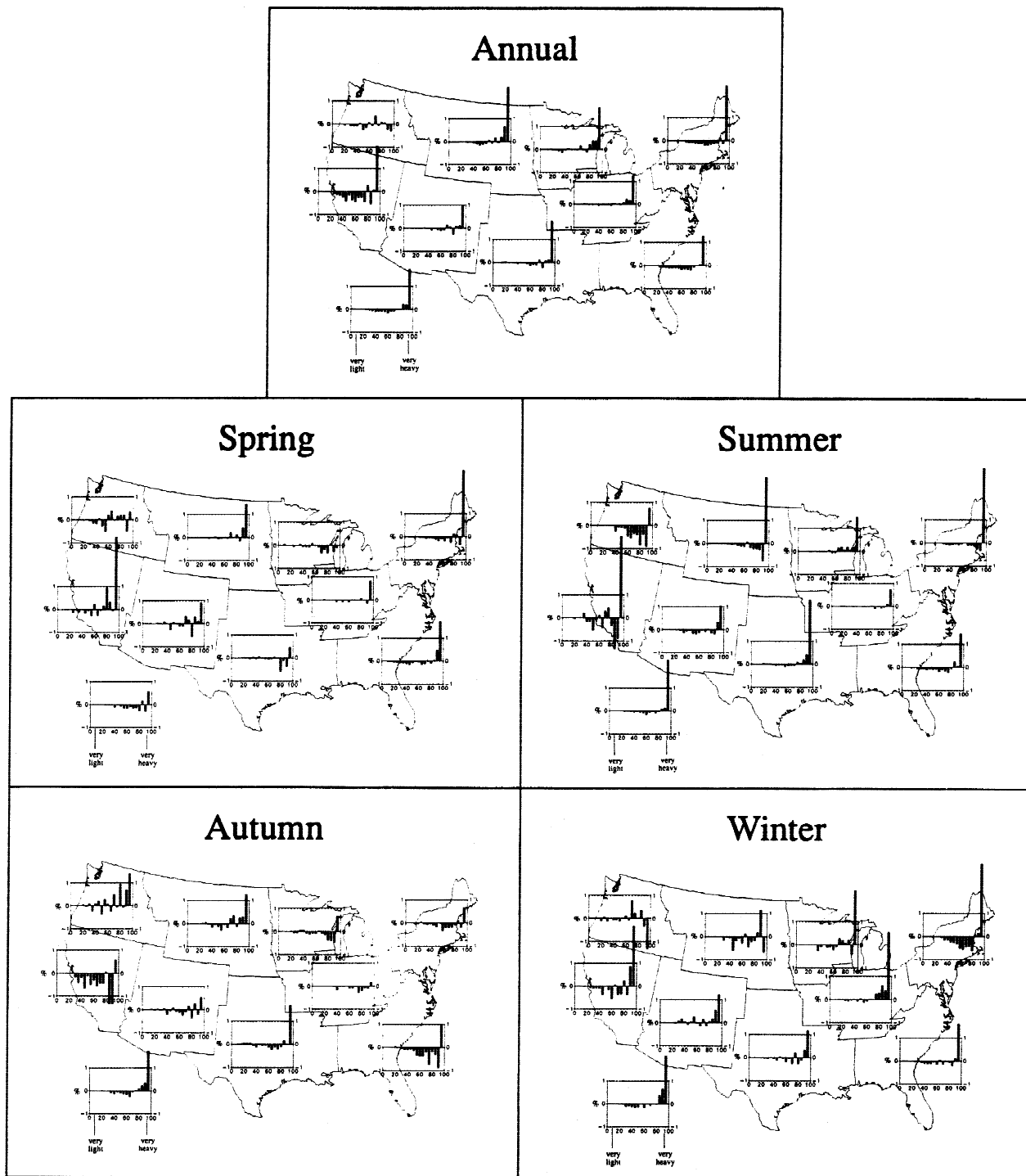


FIG. 5. The contribution to the trends in Fig. 1 attributed to trends in precipitation intensity. Trends are expressed as in Fig. 1.

## 5. Conclusions

Evaluating changes in precipitation extremes can be viewed using a variety of measures. In this analysis, simple methods to decompose the effect of changes in the frequency or probability of precipitation, and

changes in precipitation intensity have been shown to uncover significant changes in U. S. precipitation extremes. Although it has been documented in several studies that precipitation is increasing in the United States, there are a variety of ways in which such an increase could have occurred. For example, precipita-

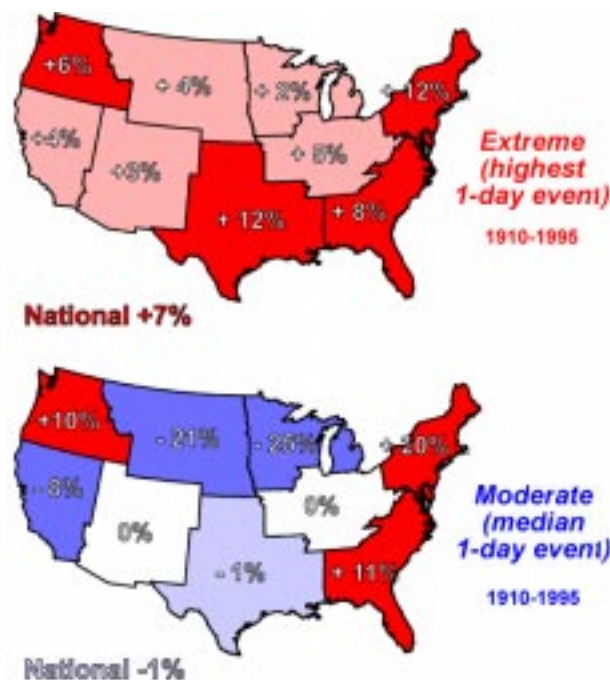


FIG. 6. Trends (1910–95) related to the highest daily year-month precipitation amount averaged throughout the year, and likewise for the medium precipitation amount. Trends are expressed as a percentage of the overall mean of the highest (median) daily year-month precipitation amount. Statistically significant trends are highlighted. The national trend is statistically significant at the  $\alpha = 0.05$  level for the highest daily year-month values.

tion could have increased because a greater number of precipitation days in selective categories of precipitation, or it could have increased without any increase in precipitation frequency, but with an increase in precipitation intensity. What this analysis revealed is that in the United States over the past century, precipitation has increased in a fairly complex manner. For example,

- Increases of total precipitation are strongly affected by increases in both frequency and intensity of heavy and extreme precipitation events.
- The probability of precipitation on any given day has increased for all categories of daily precipitation amount.
- The intensity of precipitation has increased for very heavy and extreme precipitation days only.
- The proportion of total annual precipitation derived from heavy and extreme precipitation events has increased relative to more moderate precipitation.

As more daily data becomes available through data archeology efforts, similar analyses for other areas of

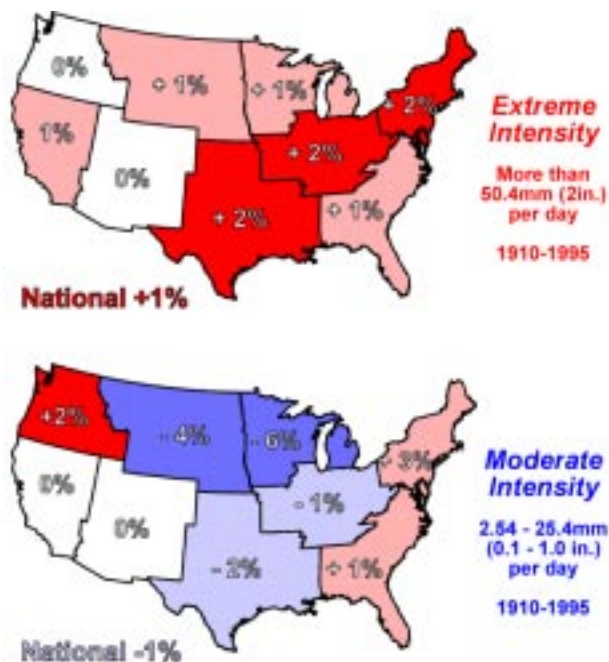


FIG. 7. Trends (1910–95) related to the proportion of total annual precipitation within various categories of precipitation. Trends are expressed as a percent change. Statistically significant trends are highlighted.

the world will provide considerable information to better understand how the source term of the hydrologic cycle has varied and changed.

## References

- Diaz, H. F., 1991: Some characteristics of wet and dry regimes in the contiguous United States: Implications for climate change detection efforts. *Greenhouse Gas-Induced Climate Change: A Critical Appraisal of Simulations and Observations*. M. E. Schlesinger, Ed., Elsevier, 269–296.
- Englehart, P. J., and A. V. Douglas, 1985: A statistical analysis of precipitation frequency in the conterminous United States, including a comparison with precipitation totals. *J. Climate*, **24**, 350–362.
- Groisman, P. Ya, and D. R. Easterling, 1994: Variability and trends of precipitation and snowfall over the United States and Canada. *J. Climate*, **7**, 184–205.
- Guttman, N. G., and R. G. Quayle, 1996: A historical perspective of U.S. climate divisions. *Bull. Amer. Meteor. Soc.*, **77**, 293–303.
- Hughes, P. Y., E. H. Mason, T. R. Karl, and W. A. Brower, 1992: United States historical climatology network daily temperature and precipitation data. Department of Energy, Oak Ridge National Lab. ORNL/CDIAC-50 NDP-42, 55 pp. plus appendixes.

IPCC, 1990: *Climate Change: The IPCC Scientific Assessment*, J. T. Houghton, G. J. Jenkins, and J. J. Ephraums, Eds., Cambridge University Press, 362 pp.

—, 1995: *Climate Change 1995: The Second IPCC Scientific Assessment*, J. T. Houghton, L. G. Meira Filho, and B. A. Callendar, Eds., Cambridge University Press, 572 pp.

Karl, T. R., R. W. Knight, and N. Plummer, 1995: Trends in high-frequency climate variability in the twentieth century. *Nature*, **377**, 217–220.

—, P. Y. Groisman, R. W. Knight, and R. R. Heim Jr., 1993: Recent variations of snow cover and snowfall in North America and their relation to precipitation and temperature variations. *J. Climate*, **6**, 1327–1344.

—, R. W. Knight, D. R. Easterling, and R. G. Quayle, 1996: Indices of climate change for the United States. *Bull. Amer. Meteor. Soc.*, **77**, 279–292.

Mearns, L. O., F. Giorgi, L. McDaniel, and C. Shields, 1995: Analysis of daily variability of precipitation in a nested regional climate model: Comparison with observations and doubled CO<sub>2</sub> results. *Global Planetary Change*, **10**, 55–78.

Nicholls, N., and A. Kariko, 1992: East Australian rainfall events: Interannual variations, trends, and relationships with the

Southern Oscillation. *Fifth Int. Meeting Stat. Climatol.*, **5**, J82–J86.

Siegal, S., 1956: *Nonparametric Statistics for the Behavioral Sciences*, McGraw-Hill, 213–222.

Yu, B., and D. T. Neil, 1991: Global warming and regional rainfall: The difference between average and high intensity rainfalls. *Int. J. Climatol.*, **11**, 653–661.

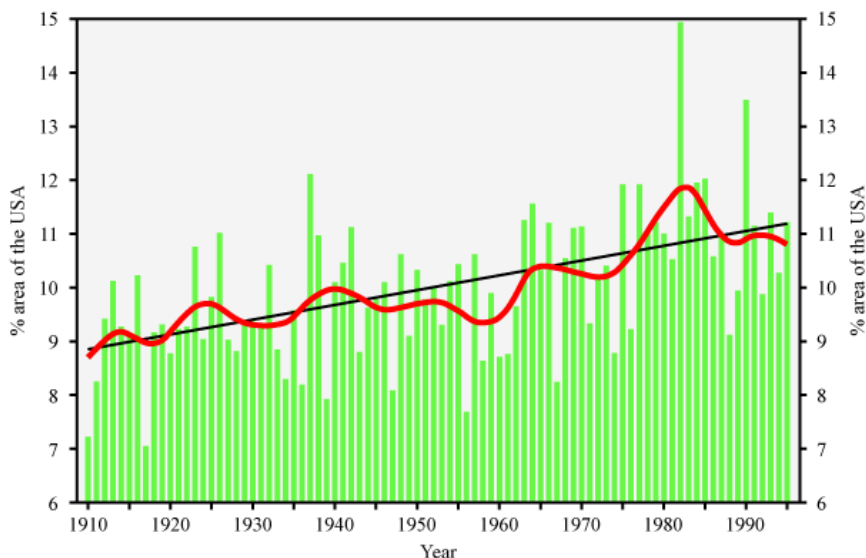


FIG. 8. Time series of the change in the area of the United States affected by a much above normal proportion of extreme precipitation events (daily precipitation exceeded 50.8

